Impacts of Anthropogenic Sound on Cetaceans

John Hildebrand
Scripps Institution of Oceanography
University of California San Diego
La Jolla, CA 92093-0205

ABSTRACT

Anthropogenic sound is created in the ocean both purposefully and unintentionally. The result is noise pollution that is high-intensity and acute, as well as lower-level and chronic. The locations of noise pollution are along well-traveled paths in the sea and particularly encompass coastal and continental shelf waters, areas that represent critical marine mammal habitat. The problem is one of isolation and a lack of awareness between humans who use the sea and marine mammals that inhabit the sea. Increased use of the sea for commercial shipping, geophysical exploration, and advanced warfare has resulted in a higher level of noise pollution over the past few decades. Informed estimates suggest that noise levels are at least 10 times higher today than they were a few decades ago. Without some effort to reduce or at least cap these noise levels, future ocean noise levels are likely to increase and further degrade the acoustic environment.

A long-term monitoring program is needed to track future changes in ocean noise. Acoustic data should be included in global ocean observing systems now being planned by U.S. and international research foundations. Data from these monitoring systems should be openly available, and accessible to decision makers in industry, in the military, and in regulatory agencies. In tandem, a database should be developed to collect, organize and standardize data on ocean noise measurements and related anthropogenic activities. Currently, data regarding shipping, seismic exploration, oil and gas production, and other marine activities are either not collected or are difficult to obtain and analyze because they are maintained by separate organizations. Marine noise measurements and anthropogenic source data should be used to develop a global model of ocean noise. An important component of model development is better understanding of the characteristics for anthropogenic noise sources such as commercial shipping, arigun arrays, and military sonar. Research should be conducted relating the overall levels of anthropogenic activity (such as the types and numbers of vessels) with the resulting noise.

Review of the evidence suggests that noise pollution is an important factor in the health of marine mammal habitats. There is sufficient evidence to conclude that high-intensity sounds are harmful and, on occasion, fatal to marine mammals. Behavioral data on marine mammal reaction to sound is complex, partially because of our meager abilities to observe marine mammal behavior in the wild. Evidence suggests that given the opportunity, marine mammals avoid high-intensity sound. Damage to marine mammal hearing due to anthropogenic sound exposure has been documented in the most extreme cases. Multiple mass-stranding events of beaked whales following high-intensity sound exposure demonstrate a repeated pattern of events. Following exposure to high-intensity sonar or airguns, beaked whales rapidly swim to the beach, and the animals die if not returned to the sea by human intervention. Those that are returned to the sea have an unknown fate. Understanding the causes and consequences of beaked whale mass stranding should be a high research priority. What is the mechanism for damage and/or disturbance?

An impediment to assessing the biological effects of ocean noise is a continued lack of knowledge about marine mammal behavioral response to sound. Behavioral data must be collected in the wild to reveal potential effects. Significant ocean noise effects may be confined to a few individuals exposed at high sound pressure levels, and/or from widespread exposure at a population level. Discerning population level effects is challenging since the observations must be conducted over broad distances and long time periods. Our lack of understanding marine mammal behavioral reaction to sound is vast and must be addressed in the face of raising ocean noise levels.

Research tools are needed to better observe marine mammal behavior in the wild. These are needed both to characterize normal behaviors and to detect changes in behavior associated with anthropogenic noise. Tools

also are needed to study marine mammal physiology in the wild. For instance, indicators of stress may be one way to assess the impact of anthropogenic noise on marine mammals. Anthropogenic ocean noise sources are primarily concentrated into a few well defined zones, at major commercial ports and along shipping lanes, in areas of oil exploration and development, and within military test and training sites. The marine mammal populations within these zones should be characterized and monitored for potential impact due to anthropogenic noise.

INTRODUCTION

There is growing concern that sound introduced into the sea by human activities has detrimental effects on marine mammals. Mounting evidence suggests that high-intensity anthropogenic sound from sonar and airguns leads to strandings and subsequent mortality of beaked whales. Although the mechanisms of injury in these events are unclear, the species affected and implicated sound levels follow a consistent pattern. A potentially more pervasive, yet more subtle, problem may be the effects on marine mammals due to increases in ambient noise levels from commercial shipping. Higher levels of ambient noise may interfere with marine mammals' ability to detect sounds, whether these are calls of conspecifics, echos from prey, or natural sounds that aid in navigation or foraging. Such noise may affect reproductive or immune functions and cause more generalized stress. The effects of other pollutants (e.g., chemicals) may be additive or synergistic with those of noise.

Sources of anthropogenic noise are becoming both more pervasive and more powerful, increasing both oceanic background sound levels and peak intensity levels. Ambient noise in the ocean has increased over the past 50 years at both at low (less than 1000 Hz) and mid-frequencies (1-20 KHz). Contributors to ambient noise are commercial shipping, defense-related activities, hydrocarbon exploration and development, research activities, and recreational activities.

Sound is an extremely efficient way to propagate energy through the ocean, and marine mammals have evolved to exploit its potential. Many marine mammals use sound as a primary means for underwater communication and sensing. Toothed whales have developed sophisticated echolocation systems to sense and track the presence of prey and engage in complex exchanges of vocalizations with conspecifics. Baleen whales have developed long-range acoustic communication systems to facilitate mating and social interaction. Some produce intricately patterned songs that continue for hours or days. Marine mammals may use sound from natural sources as a guide for navigation, prey detection, and avoidance of predation. The sound environment of the ocean is an important aspect of marine mammal habitat and we can expect marine mammals to choose their locations and modify their behavior based, in part, on natural and anthropogenic sounds.

Human presence at sea is normally on the surface, and the sounds that we produce within the water are rarely given much consideration. The air-sea interface creates a substantial sound barrier. Sounds waves in the water are reduced in intensity by more than a factor of a thousand when crossing the air-sea boundary. This means that we are effectively insulated from the noise produced by rotating propellers that drive our ships or by high-intensity sonars used to measure the depth or probe the interior of the sea. The conflict between human and marine mammal use of the sea is fundamentally a consequence of the fact that we do not inhabit the same sound environment. Marine mammals live with their ears in the water, and we live, even at sea, with our ears in the air.

A notable exception is when the military uses submarines, and stealth is required. Minimization of sound production then becomes crucial to survival. Reduction in noise has been achieved by placing rotating machinery on isolating mounts and by designing efficient propellers that thrust without unnecessary accompanying vibrations and cavitations. Thus, when it has seemed important to keep the sea quiet, the necessary technology has been developed and made available. .

NOISE LEVELS IN THE OCEAN

Sound is a vibration or acoustic wave that travels through some medium, such as air or water. Acoustic waves can be described either by the speed at which a small piece of the medium vibrates, called the particle velocity, or by the corresponding pressure associated with the vibration. Frequency is the rate of vibration, given in Hertz (Hz) or cycles per second; we perceive frequency as the pitch of the sound. A tone is a sound of a constant frequency that continues for a substantial time. A pulse is a sound of short duration, and it may include a broad range of frequencies.

In water, sound waves are typically measured by their pressure using a device called a hydrophone. When discussing ambient noise, the implicit assumption is that sound pressure fluctuations are being described, although it is not clear whether a particular marine organism is able to sense particle velocity or acceleration. Sound pressure is measured in Pascals (Pa) in the international system of units (SI), although it is expressed in bars by the geophysical community (1 Pa = 10^{-5} bar). Since mammalian hearing and sound production cover a large range of pressure values, sound pressure level (SPL) is usually measured on a logarithmic scale called the decibel (dB), and compared against a 1 µPa reference (P_o) for underwater sound as follows:

$$\text{SPL dB re: 1 µPa} = 10 \log_{10} (P / P_o)^2$$

$$\text{SPL dB re: 1 µPa} = 20 \log_{10} (P / P_o)$$

Pressure is squared in the above expression as a proxy for acoustic intensity, that is, the power flow per unit area in the sound wave, with units of watts/m^2. Sound intensity is the product of pressure (P) and particle velocity (v). Acousticians working in one medium (water or air) use the fact that for plane waves the pressure and particle velocity are related by the characteristic impedance (Z) of the medium as follows:

$$Z = P / v$$

This allows the acoustic intensity (I) to be related to the pressure squared, divided by the impedance:

$$I = 10 \log_{10} (P^2 /(Z^* I_o))$$

Acoustic power is obtained by integrating intensity over some area, and acoustic energy is obtained by integrating the power over some time period. The same acoustic energy can be obtained from a high-intensity source over a short time (impulse) and a low-intensity source over a long time (continuous wave).

When sound propagates from water into air, there is a 30 dB (1000 x) decrease in acoustic intensity because the characteristic impedance of water is much greater than that of air. This means that sounds made by a high-intensity underwater source (such as a sonar) are not transmitted into the air with the same intensity. In essence, sailors and passengers on ships are protected from the sounds that they generate. Without the air-sea boundary for protection, there would be a strong incentive to protect human hearing from the noise of sonars and cavitating propellers on ships. (Note that for sound in air a different reference level is used, P_o = 20 µPa, and this is a source of much confusion when comparing underwater and in-air sounds.)

Underwater sounds are classified according to whether they are transient or continuous. Transient sounds are of short duration, often called pulses, and they may occur singly, irregularly, or as part of a repeating pattern. For instance, an explosion represents a single transient, whereas the periodic pulses from a ship's sonar are patterned transients. Underwater sounds also can be classified as continuous, that is, they occur without a pause or hiatus. Continuous sounds are further classified as periodic, such as the sound from rotating machinery or pumps, or aperiodic, such as the sound of a ship breaking ice.

Pulsed sounds are measured in terms of their total energy, rather than just their pressure or intensity. Pressure and power measures are difficult to interpret for a brief pulse since they depend on the averaging time. Energy is proportional to the time integral of the squared pressure, described in the units μPa^2-s. For brief pulses, energy in dB re: μPa^2-s is less than peak squared pressure values in dB μPa^2. As others have warned, better standardization of measurement methods for pulsed underwater sounds is urgently needed to permit meaningful comparisons (Greene 1995).

Ambient noise in the ocean is the background sound that incorporates the broad range of individual sources, some identified and others not. Ocean noise may come both from distant sources, such as ships, or from nearby sources, such as the waves breaking directly above the listener. Although ambient noise is always present, the individual sources that contribute to it do not necessarily create sound continuously.

Natural ocean acoustic environment

The ambient acoustic environment of the ocean is highly variable. At a given time and place, a broad range of sources may be combined. In addition, conditions at a particular location may affect how well ambient sounds are received (e.g., sound propagation, water depth, bathymetry, and depth). Natural phenomena known to contribute to oceanic ambient noise include: (a) wind, sea state and swell patterns, (b) bubble distributions, (c) currents and turbulence, (d) seismic activity, (e) precipitation, (f) ice cover and activity, and (g) marine life.

Wind, Waves and Ice

Ocean surface motions due to wind, sea state and swell patterns are the dominant physical mechanisms for natural sound in the ocean. Noise is primarily associated with wind acting on the surface, causing wave activity. In the absence of anthropogenic and biological sound, ambient noise is wind dependent over an extremely broad frequency band from below 1 Hz to at least 100 kHz. At frequencies below 10 Hz, interactions of surface gravity waves are the dominant mechanisms for sound generation. Across the remainder of the band from 10 Hz – 100 kHz, oscillating bubbles in the water column are the primary noise source, both as individual bubbles and as bubble clouds.

In early descriptions, ocean noise was related to sea state (Knudsen et al. 1948). By this theory, noise levels increase with increasing sea state by the same amount across the entire frequency band from 1 kHz to 100 kHz. More recent work has suggested that noise is better correlated with wind speed than with sea state or wave height. The correlation between noise and wind speed allows for more accurate prediction, as sea states are more difficult to estimate than wind speeds. In the open ocean, the noise of breaking waves is correlated with wind speed. Spilling and plunging breakers raise underwater sound levels by more than 20 dB across the band from 10 Hz to 10 kHz (Wilson et al. 1985). Precipitation is another factor that can increase ambient noise levels by up to 35 dB across a broad band of frequencies from 100 Hz to more than 20 kHz (Nystuen and Farmer 1987). Ice cover alters the ocean noise field depending on its type and degree, for instance, whether it is shore-fast pack ice, moving pack ice, or at the marginal ice zone (Milne 1967). Shore-fast pack ice isolates the water column from the effects of wind, and results in a decrease in ambient noise of 10-20 dB. Sounds from ice cracking, however, may increase noise levels by as much as 30 dB. Ice cracking can generate broadband pulses up to 1 kHz lasting for a second or longer. Interaction of ocean waves with the marginal ice zone may raise noise levels by 4-12 dB (Diachok and Winokur 1974).

Earthquakes

Earthquakes and thunder are examples of transient natural sound sources. Underwater recordings of thunder from storms 5 to10 km distant show peak energy between 50 and 250 Hz, up to 15 dB above background levels (Dubrovsky and Kosterin 1993). Seismic energy from undersea earthquakes couples into the ocean and is called T-phase (tertiary) in addition to the usual P-phase (primary) and S-phase (secondary) seismic waves that are observed on land. At ranges of less than 100 km, T-phase energy can have frequencies greater than 100 Hz, with peak energy at 5-20 Hz. It can be as much as 30-40 dB above background noise, with a sharp onset, and can last from a few seconds to several minutes (Schreiner et al. 1995).

Anthropogenic Sound

Human activity in the marine environment is an important component of the total oceanic acoustic background. Sound is used both as a tool for probing the ocean and as a byproduct of other activities. Anthropogenic noise sources vary in space and time, but may be grouped into general categories: (a) large commercial ships, (b) airguns and other seismic exploration devices, (c) military sonars, (d) ship-mounted sonars, (e) pingers, (f) acoustic harassment devices (AHDs), (g) polar ice-breakers, (h) offshore drilling implements, (i) research sound sources, and (j) small ships.

Commercial Shipping

At low frequencies (5 to 500 Hz), commercial shipping is the major contributor to noise in the world's oceans. Distant ships contribute to the background noise over large geographic areas. The sounds of individual vessels are often spatially and temporally indistinguishable in distant vessel traffic noise. Noise from vessel traffic at high latitudes is particularly efficient at propagating over large distances because in these regions the oceanic sound channel (zone of most efficient sound propagation) reaches the ocean surface.

Ships generate noise primarily by (a) propeller action, (b) propulsion machinery, and (c) hydraulic flow over the hull. Propeller noise is associated with cavitation (Ross 1987, 1993), the creation of voids from zones of pressure above the ambient. The collapse of these voids generates sound. Cavitation creates both broadband noise and tonal sounds, as it may be modulated by blade-passage frequencies and their harmonics (the blade lines). The broadband and tonal components produced by cavitation account for 80-85 percent of ship-radiated noise power (Ross 1987). Propeller noise may be also generated by unsteady propeller blade-passage forces. Additional ship noise results from propulsion machinery such as diesel engines, gears, and major auxiliaries such as diesel generators.

Particular vessels produce unique acoustic signatures associated with noise source levels and frequency bands. Sharp tonal peaks produced by rotating and reciprocating machinery such as diesel engines, diesel generators, pumps, fans, blowers, hydraulic power plants, and other auxiliaries often are seen in these acoustic signatures. Hydrodynamic flow over the ship's hull and hull appendages is an important broadband noise-generating mechanism, especially with increased ship speed. At relatively short ranges and in isolated environments, the spectral characteristics of individual ships can be discerned. At distant ranges in the open ocean, multiple ships contribute to the background, and the sum of many distant sources creates broad spectral peaks of noise in the 5 to 500-Hz band.

Models for representative noise spectra for different classes of ships have been developed by the U.S. Navy. The Research Ambient Noise Directionality (RANDI) model (Wagstaff 1973; Schreiner 1990; Breeding 1993) uses ship length and speed as well as an empirically derived power law to determine the broadband (5-500 Hz) spectral level for various classes of vessels. Peak spectral densities for individual ships range from 195 dB re $\mu Pa^2/Hz$ @ 1 m for fast moving supertankers, to 140 dB re $\mu Pa^2/Hz$ @ 1 m for small fishing vessels. Source-level models have been also developed for the propeller tonal blade lines, occurring at 6-10 Hz for most of the world's large merchant fleet (Gray and Greeley 1980). Small vessels do not contribute significantly to the global ocean acoustic environment, but may be important local sound sources. Examples of noise levels for whale-watching boats are presented by (Au and Green 2000) and (Erbe 2002). A recent study of noise levels from small powerboats suggests peak spectral density levels in the 350-1200 Hz band of 145-150 dB re $1\mu Pa^2/Hz$ @ 1 m (Bartlett and Wilson 2002).

Vessel traffic is not uniformly distributed. The major commercial shipping lanes follow great circle routes, or follow coast lines to minimize the distance traveled. Dozens of major ports and "megaports" handle the majority of the traffic, but in addition hundreds of small harbors and ports host smaller volumes of traffic. The U.S. Navy defines 521 ports and 3,762 traffic lanes in its catalog of commercial and transportation marine traffic (Emery et al. 2001). Vessels found in areas outside major shipping lanes include fishing vessels, military ships, scientific research ships, and recreational craft – the last typically found near shore.

Lloyd's Register of the world's commercial fleet for the year 2001 listed 92,817 vessels (NRC 2003). The principal types (their numbers in parentheses) are cargo/passenger transport (34,704), fishing (23,841), towing/dredging (13,835), oil tankers (10,941), bulk dry transport (6,357), and offshore supply (3,139). Gross tonnage may be a more important index of noise production than vessel numbers. From that perspective, oil tankers and bulk dry transport vessels represent nearly 50 percent of the total tonnage, but less than 8 percent of the total number of vessels.

The numbers of recreational craft are poorly documented. Some information on the number of U.S. boat registrations, by state and category, is available from the National Marine Manufacturer's Association (2003). The vessel categories are outboard, inboard, sterndrive, personal watercraft, sailboats, and miscellaneous.

Vessel operation statistics indicate steady growth in vessel traffic over the past few decades (Mazzuca 2001). There has been an increase both in the number of vessels and in the tonnage of goods shipped. For example, a 30 percent increase has occurred in the volume of goods shipped by the U.S. fleet (by flag and ownership) over the past 20 years (U.S. Maritime Administration, 2003). Oceanic shipping is an efficient means of transporting large quantities of goods and materials globally. The globalization of economic infrastructure means that more raw materials, as well as finished goods, require long-distance transport. The economic incentives for oceanic shipping are strong, and in the near term, there is no viable alternative for transporting large-tonnage materials to distant global locations.

The bulk of U.S. waterborne trade is conducted through a few ports (Table 1). For instance, the combined ports of Los Angeles and Long Beach carry 37 percent of the total (U.S. Maritime Administration 2003). Within the U.S. Exclusive Economic Zone, this concentrates the noise from shipping into the regions adjacent to these ports and their approaches. Since the Southern California Bight is a particularly productive habitat for marine mammals, the concentration of shipping noise within this region is a cause for concern. Significant concentrations of shipping traffic also occur in New York (13 percent) and the Puget Sound area (8 percent).

Table 1: U.S. Foreign Waterborne Trade, Calendar Year 2002
Units are thousands of Twenty-Foot-Equivalent (TEU) containers.
Source: U.S. Maritime Administration (2003)

Rank	U.S. Port	Total	Export	Import
1	Los Angeles	4,060	866	3,194
2	Long Beach	3,184	717	2,467
3	New York	2,627	747	1,879
4	Charleston	1,197	521	676
5	Savannah	1,014	453	561
6	Norfolk	982	431	551
7	Oakland	979	469	482
8	Houston	851	430	420
9	Seattle	850	338	512
10	Tacoma	769	278	491
TOTAL		19,729	6,814	12,916

Plans exist for a new generation of container ship that is significantly faster (36 knots) and has a larger carrying capacity (1,400 Twenty-Foot-Equivalent containers) (Morrison 2000). These plans involve cross-over ship designs from the fast-ferry industry and appear technically feasible. The economic viability of fast shipping depends on the balance between the additional fuel and other expense for shipping the goods, and the value of the goods being shipped. When the cost of greater ship speed is offset by the value gained from diminished time spent in shipping, then faster container ships will become economically competitive. With respect to noise, these vessels will generate more low-frequency noise than current vessel designs owing to their greater speed and propulsive power.

Seismic Exploration

Seismic reflection profiling uses high-intensity sound to image the earth's crust. It is the primary technique for finding and monitoring reserves of oil and natural gas. Seismic reflection profiling is used by academic and government groups to gather information on crustal structure, for the purpose of understanding the origin and tectonic history of the earth's crust.

Arrays of airguns are the sound-producing elements in seismic reflection profiling (Dragoset 1984, 2000). Airguns release a specified volume of air under high pressure, creating a sound pressure wave from the expansion and contraction of the released air bubble. To yield high intensities, multiple airguns are fired with precise timing to produce a coherent pulse of sound. Oil industry airgun arrays typically involve 12 to 48 individual guns, operate at pressures of 2000 psi, and are dispersed over a 20 m by 20 m region, typically towed about 200 m behind a vessel. The pressure output of an airgun array is proportional to (1) its operating pressure, (2) the number of airguns, and (3) the cube root of the total gun volume. For consistency with the underwater acoustic literature, airgun-array source levels are back-calculated to an equivalent source concentrated into a one-meter-radius volume, yielding source levels as high as 256 dB re 1µPa @ 1 m for the Root-Mean-Square (RMS) output pressure (Greene and Moore 1995). This source level predicts pressures in the far-field of the array, but in the near-field the maximum pressure levels encountered are limited to 235-240 dB re 1µPa. The far field pressure from an airgun array is focused vertically, being about 6 dB stronger in the vertical direction than in the horizontal direction for typical arrays. The peak pressure levels for industry arrays are in the 5-300 Hz range. The guns are towed at speeds of about 5 knots and are typically fired about every 10 seconds. A seagoing seismic-reflection operation includes a series of parallel passes through an area by a vessel towing an airgun array as well as 6-10 seismic receiving streamers. A recent practice is the use of repeated seismic reflection surveys for "time-lapse" monitoring of producing oil fields.

Offshore oil and gas exploration and construction activities occur along continental margins. Currently active areas include northern Alaska and northwestern Canada, eastern Canada, the U.S. and Mexican Gulf of Mexico, Venezuela, Brazil, West Africa, South Africa, North Sea, Middle East, northwestern Australia, New Zealand, southern China, Vietnam, Malaysia, and Indonesia. New areas of exploration include the deepwater U.S. Gulf of Mexico and deepwater West Africa, both of which have seen activity in the past 5 to10 years.

Sonar

Sonar systems intentionally create acoustic energy to probe the ocean. They seek information about objects within the water column, at the sea bottom, or within the sediment. Active sonar emits high-intensity acoustic energy and receives reflected and/or scattered energy. A wide range of sonar systems are in use for both civilian and military applications. For purposes of discussion, sonar systems can be categorized as low-frequency (< 1000 Hz), mid-frequency (1 – 20 kHz), and high-frequency (> 20 kHz).

Military sonars are used for target detection, localization, and classification. They generally cover a broader frequency range with higher source levels than civilian sonars. They are operated during both training exercises and combat operations. Because far more time is spent in training than in combat, training exercises may be the primary context in which marine mammals are exposed to military sonar. Low Frequency Active (LFA) sonars are used for broad-scale surveillance; they are designed to allow submarine tracking over scales of many hundreds to thousands of kilometers. Specialized support ships are used to deploy LFA sonars, which consist of arrays of source elements suspended vertically below the ship. The U.S. Navy's Surveillance Towed Array Sensor System (SURTASS) LFA sonar uses an array of 18 projectors operating in the frequency range of 100 to 500 Hz, with 215 dB re 1µPa @ 1 m source level for each projector (Johnson 2002). These systems are designed to project beams of energy in a horizontal direction. The effective source level of an LFA array, when viewed in the horizontal direction, can be 235 dB re 1µPa @ 1 m or higher. The signal includes both continuous-wave (CW) and frequency-modulated (FM) components with a bandwidth of approximately 30 Hz. A ping sequence can last 6 to 100 seconds, with a time between pings of 6 to 15 minutes and a typical duty cycle of 10 to 15 percent. Signal transmissions are emitted in patterned sequences that may last for days or weeks.

Mid-frequency tactical Anti-Submarine Warfare (ASW) sonars are designed to detect submarines over several tens of kilometers. They are incorporated into the hulls of submarine-hunting surface vessels such as destroyers, cruisers, and frigates (see Table 2). There are 117 of these sonars on U.S. Navy ships currently in active service, and equivalent systems in allied navies (e.g., British, Canadian, French). The AN/SQS-53 is the most advanced surface ship ASW sonar used by the U.S. Navy. The AN/SQS-53C sonar generates frequency-modulated pulses of 1-2 second duration in the 1-5 kHz band, at source levels of 235 dB re 1µPa @ 1 m or higher (Evans and England 2001). These sonars emit beams of sound in the horizontal direction. The AN/SQS-53C is designed to perform direct-path ASW search, detection, localization, and tracking from a hull mounted transducer array of 576 elements housed in a bulbous dome located below the waterline of the ship's bow. These systems are used to track both surface and submerged vessels, often picking up surface ships at greater range than most radar systems.

Table 2. US Navy surface ships with Anti-Submarine Warefare active sonars.

Type of Ship	Class	Type of Sonar	Number in use
Cruiser	Ticonderoga	SQS-53	27
Destroyer	Spruance	SQS-53	11
Destroyer	Arleigh Burke	SQS-53	49
Frigate	Oliver Hazard Perry	SQS-56	30
Total			117

Other mid-frequency military sonars in use by the Navy include depth sounders and communication sonars for interplatform information exchange or device activation.
High-frequency sonars are incorporated either into weapons (torpedoes and mines) or weapon countermeasures (mine countermeasures or anti-torpedo devices). They are designed to operate over ranges of a few hundred meters to a few kilometers. Mine-hunting sonars operate at tens of kHz for mine detection and above 100 kHz for mine localization. These sonars are highly directional and use pulsed signals. Other high-frequency military sonars include sidescan sonar for seafloor mapping, generally operated at frequencies near 100 kHz.

Over the past decade, there has been a trend in the U.S. Navy to emphasize training operations in coastal and shallow-water settings. There are currently plans to construct shallow-water training ranges on both the U.S. West and East Coasts. The use of active sonar in these settings means that large numbers of marine mammals may be exposed to high-intensity sonar.

Commercial sonars are designed for fish finding, depth sounding, and sub-bottom profiling. They typically generate sound at frequencies of 3 to 200 kHz, with only a narrow frequency band generated by an individual sonar system. Source levels range from 150-235 dB re 1µPa @ 1 m. Commercial depth sounders and fishfinders are typically designed to focus sound into a downward beam. Depth sounders and sub-bottom profilers are operated primarily in nearshore and shallow environments, however, fish finders are operated in both deep and shallow areas.

The acoustic characteristics of small-scale commercial sonars are unlikely to change significantly in the future since they are limited by several key physical properties. At the low-frequency end (about 3 kHz), they are limited by the physical dimensions of the transducers. At the high-frequency end (200 kHz) they are limited by severe attenuation of sound. Likewise, the maximum power level that can be emitted by a single transducer (200 dB re 1µPa @ 1 m) is limited by cavitation at shallow depths of operation. Higher power levels can be achieved by constructing arrays of sensors on the hull of the vessel. For example, multibeam echosounding systems (e.g., SeaBEAM or Hydrosweep) form narrow directional beams of sound and are used for precise depth sounding. Using hull-mounted arrays of transducers, these systems can achieve 235 dB re 1µPa @ 1 m source levels and are typically operated at 12-15 kHz in deep water, and at higher frequencies (up to 100 kHz) in shallow water.

A significant fraction of the 80,000 vessels in the world's commercial fleet and the 17 million small boats owned in the US are equipped with some form of commercial sonar. Sonar is an extremely efficient means for fish finding and depth sounding/sub-bottom profiling, and new applications may lead to even greater proliferation of these systems.

Research in underwater acoustic propagation and acoustical oceanography often involves use of sound sources. Almost all of these programs are sponsored by the Office of Naval Research, and the information obtained is of value for improving military sonar systems. The sound sources used for these studies are either commercially available transducers or systems specially designed to meet specific research requirements. A wide variety of signals, bandwidths, source levels, and duty cycles are transmitted during these projects. The spatial extent of most experiments is tens of kilometers, but basin-scale projects such as the Acoustic Thermometry of Ocean Climate (ATOC) program have also been undertaken.

The ATOC (later the North Pacific Acoustic Laboratory [NPAL]) project was initiated in the early 1990s to study ocean warming, and received much attention from regulatory agencies, the public, and the scientific community due to concerns regarding the potential impact of its sound source on marine mammals (Baggeroer et al. 1998). This program was extensively discussed in two National Research Council reports (NRC 1994, 2000). The ATOC source has a 195 dB re 1µPa @ 1 m level and is deployed at 939 m, near the axis of the deep sound channel (Howe 1996). It is designed to study the entire North Pacific basin, with the sounds being received by the U.S. Navy's fixed hydrophone arrays. The transmitted signal is centered at 75 Hz with a bandwidth of 37.5 Hz. It broadcasts on 4-hour intervals with a "ramp-up" period of 5 minutes and a full power signal duration of 20 minutes. The long time frame for operation of this experiment was a key aspect that led to questions regarding its potential impacts on marine mammals (Potter 1994).

Another basin-scale sonar research project uses drifting sources (Rossby et al. 1986), called SOFAR or RAFOS floats. These devices drift at depth and periodically emit a high-intensity tone (195 dB re 1µPa @ 1 m) that is frequency swept at 200-300Hz or a CW signal at 185-310 Hz with durations of 120 sec or more. The sounds are detected at distant receivers and their timing is used to determine the float location and therefore its drift, as a proxy for deep currents.

Acoustic Deterrent Devices

Acoustic deterrent devices (ADD) use sound in an effort to repel marine mammals from fisheries activities. The idea behind these devices is that they keep marine mammals away by introducing a local acoustic annoyance. Pingers are used in some fisheries to reduce the bycatch of marine mammals. These are typically low-power ADDs with source levels of 130 – 150 dB re 1µPa @ 1 m. Acoustic harassment devices (AHD) are used to reduce depredation by marine mammals on caught or cultured fish. These are high-powered devices with source levels of 185 – 195 dB re 1µPa @ 1 m. Both pingers and AHDs have frequencies in the 5 – 160 kHz band, and generate pulses lasting from 2 – 2000 msec. To reduce habituation, a single device may transmit a variety of waveforms and have pseudo-random time intervals between transmissions.

Pingers have been shown to be effective in reducing bycatch, at least for some marine mammal species in some settings (Kraus et al. 1997; Culik et al. 2001; Bordino et al. 2002). A trial of pinger use in the California drift gillnet fishery for swordfish and sharks showed that for both cetaceans and pinnipeds, the entanglement rate in nets with pingers was only one third of what it was in nets without these devices (Barlow and Cameron 2003). Likewise, a large-scale trial of pingers in Danish gillnet fisheries showed a reduction in bycatch of harbor porpoises (Larsen 1997; Vinther 1999).

Concerns have arisen that use of AHDs in aquaculture facilities leads to unintended displacement of marine mammals in the cases of killer whales (Morton and Symonds 2002) and harbor porpoises (Olesiuk et al. 2002) in the vicinity of salmon farms off British Columbia. Likewise, there are concerns that widespread use of AHDs may lead to the exclusion of porpoises from important feeding habitat (Johnston 2002). AHDs have sufficiently high source levels that they could result in hearing damage to marine mammals exposed at close range.

Explosions

There are two classes of man-made explosions in or over the ocean: nuclear and chemical. Until the advent of the Comprehensive Test Ban Treaty, nuclear devices were tested regularly in the ocean, in the atmosphere above the ocean, or on oceanic islands. The most recent series of oceanic tests was conducted by France in 1995-1996 on the islands of Fangataufa and Mururoa in the South Pacific. There is currently a low probability of continued ocean testing of nuclear devices although this situation could change with geopolitical developments over the coming years or decades.

Nuclear explosion are extremely strong sources of underwater sound. It is likely that past tests had significant impacts on marine mammals in the vicinity of the test sites. No monitoring data are available, however, to document impacts of nuclear tests on marine mammals. To ensure compliance with the test ban treaty, an international monitoring system is being implemented, including a series of hydrophone- and island-based seismic stations to detect high-intensity sounds (www.ctbto.org). This information is transmitted, in real time, to the International Data Centre where analysts evaluate the data for indications of nuclear explosions. Physical characteristics of the oceans allow the sounds of such explosions to travel for extremely long distances with little energy loss, and monitoring is conducted over a large fraction of the world's oceans with a small number of stations. The network designed for ocean monitoring contains 11 stations located primarily in the Southern Hemisphere.

Clemical explosions are more portable and more easily conducted in an ocean setting. They have been used for oceanic research, for construction, and for military testing. A surprisingly large number (300-4000 per month) of underwater explosions were reported in the North Pacific during the 1960's (Spiess et al. 1968). In the past, chemical explosions were commonly used for marine seismic exploration, but they have been replaced by airgun arrays that provide a more reliable source signature. Chemical explosions continue to be used in the construction and removal of undersea structures, primarily by the oil industry, but the frequency of shot detonation presumably has decreased over the past few decades.

New classes of military vessels undergo tests, called ship-shock trials, to determine their ability to withstand explosions (Commander_Naval_Air_Warfare_Center 1994). During a ship-shock trial, a large chemical explosion (e.g. 10,000 lb) is detonated near the vessel's hull, while measurements of hull stress are conducted. Ocean explosions are also conducted by other Navy programs, such as the "Sinkex" program that sinks retired ships using torpedos or other chemical explosions. Weapons are tested during development, and operational stores are test-fired to monitor their military readiness. During the recent Iraq war, Navy SEA LS disposed of a dozen 500 pound sea mines confiscated from the Iraqi Navy by simultaneously detonating them in the Persian Gulf, a blast that could be heard 50 miles away in Kuwait (Dao 2003).

The spectral and amplitude characteristics of chemical explosions vary with the weight of the charge and the depth of the detonation. The RMS source level of the initial shock wave, a large component of the energy, is given by

$$SL\,(\text{dB re } 1\mu\text{Pa @ 1 m}) = 269\text{ dB} + 7.53 * \log(w),$$

where w is the charge weight in pounds (Urick 1975). For instance, 100 lb of TNT would produce a shockwave SL of 284 dB re 1µPa @ 1 m with almost constant frequency content from 10 to 1000 Hz. The energy from the bubble pulse oscillations will contribute approximately 5 additional dB of source level, yielding a total SL of 274 dB re 1µPa @ 1 m. Research on blast damage to animals suggests that the mechanical impact of a short duration pressure pulse (positive acoustic impulse) is best correlated with organ damage (Greene and Moore 1995).

Industrial Activities and Construction

Industrial activities and construction both in the ocean and along the shoreline can contribute to underwater noise. Examples include coastal power plants, pile driving, dredging, tunnel boring, power-generating wind mills, and canal lock operations (Greene and Moore 1995). The coupling of these sounds into the marine environment is poorly understood, but it is generally more efficient at low frequencies.

Marine dredging is commonly conducted in coastal waters to deepen channels and harbors, reclaim land, and mine seabed resources. Reported source levels for dredging operations range from 160 to 180 dB re 1µPa @ 1 m for 1/3 octave bands with peak intensity between 50 and 500 Hz (Greene and Moore 1995).

Oil and gas activities that generate marine noise include drilling, offshore structure emplacement and removal, and production. The associated noise levels from drilling, structures, and production are typically lower than those from seismic surveying. Sound pressure levels associated with drilling are the highest with maximum broadband (10 Hz to 10 kHz) energy of about 190 dB re 1µPa @ 1 m. Drill-ship noise comes from both the drilling machinery and the propellers and thrusters for station-keeping. Jack-ups are the most commonly used offshore drilling devices, followed by platform drill rigs. Drilling generates ancillary noise from the movements of supply boats and support helicopters. Emplacement of offshore structures creates localized noise for brief time periods. Powerful support vessels are used to transport these large structures from the point of fabrication to the point of emplacement. This activity may last for a few weeks and may occur 8 to 10 times a year worldwide. Additional noise is generated during oil production activities, which include borehole casing, cementing, perforating, pumping, pipe laying, pile driving, and ship and helicopter support. Production activities can generate source levels as high as 135 dB re 1µPa at 1 km from the source (Greene and Moore 1995) which suggests as much as 195 dB re 1µPa @ 1 m with peak levels at 40 to 100 Hz.

Oil and gas production is moving from shallow-water settings into water depths of up to 3000 m. Deep-water drilling and production have the potential to generate greater noise than shallow-water production, owing to the use of drill ships and floating production facilities. This noise may be more easily coupled into the deep sound channel for long-range propagation. The worldwide count of offshore mobile drill rigs in use fluctuates with business conditions, but there are an increasing number of drill rigs available, with an approximate 10 percent increase over the past five years.

Comparison and summary of anthropogenic sound sources

The anthropogenic sound sources discussed above are summarized by source level and other parameters in Table 3, ordered by their relative potential for large-scale exposure of marine mammals to high-intensity sound. Underwater nuclear tests and ship-shock trials produce the highest overall sound pressure levels, sufficient to cause physical damage, yet these are rare events and so may be assumed to have limited population-level impacts. Military SURTASS-LFA sonars and large-volume airgun arrays both have high SPLs. The long ping lengths and nearly continuous duty cycle of LFA sonars increase their likelihood of exposing marine mammal populations on a basin-scale. Both the SURTASS-LFA and airgun arrays have dominant energy at low frequencies, where long-range propagation is likely. Tactical military sonars (such as the 53C) have shorter ping durations and more moderate duty cycles than LFA sonars; they also operate at mid-frequencies, where propagation effects limit their range. Concern for the impact of these sonars is for local settings, particularly where deep-diving animals may be present (as discussed later in this paper). Commercial supertankers are arguably the most ubiquitous high-intensity sound source, with more than 10,000 vessels operating worldwide. Concern with these noise sources will be concentrated near major ports and along the most heavily utilized shipping lanes. The moored research sound source for the ATOC project is an equivalent source level to a supertanker although it operates on a much lower duty cycle. Acoustic harassment devices have source levels of concern for long-term hearing damage, and may displace marine mammals from important habitat. Multibeam hull-mounted echo-sounders have a high source level, but their narrow beam widths and mid-frequency character limit their range and the ensonified area. Research acoustic floats (RAFOS) produce a moderately high source level but are operated at a very low duty cycle. Fishing vessels and acoustic deterrent devices have moderate source levels but may represent at least local acoustic annoyances, although in the case of ADDs there is a significant benefit from the reduction of marine mammal bycatch.

TABLE 3. Comparison of anthropogenic underwater sound sources ordered by their potential for marine mammal high-intensity sound exposure.

Sound Source	**SPL** dBre 1µPa @1m	**Ping Energy** (dB re $1\mu Pa^2*s$)	**Ping Duration**	**Duty Cycle** (%)	**Peak Frequency** (Hz)	**Band Width** (Hz)	**Direct-ionality**
Underwater Nuclear Device (30 kilo-ton)	328	?	1000 s	Inter-mittant	Low	Broad	Omni
Ship Shock Trial (10,000 lb TNT)	299	?	100 s	Inter-mittent	Low	Broad	Omni
Military Sonar (SURTASS/LFA)	235	243	6 – 100 s	10	250	30	Horizontal
Airgun Array 2000 psi and 8000 in^3	256	241	30 ms	0.3	50	150	Vertical
Military Sonar (53C)	235	232	0.5 – 2 s	6	2,600-3,300	Narrow	Horizontal
Super Tanker 270 m long	198		CW	100	23	5-100	Omni
Research Sonar (ATOC Source)	195		20 minutes	8	75	37.5	Omni
Acoustic Harrassment Device	185	185	0.5 - 2 s	50	10,000	600	Omni
Multibeam (Echosounder Hull-mounted)	235	218	20 ms	0.4	12,000	Narrow	Vertical
Research Sonar (RAFOS float)	195		120 s	small	250	100	Omni
Fishing Vessel 12 m long (7 knots)	150		CW	100	300	250-1000	Omni
Acoustic Deterrent Device (AquaMark300)	132	127	300 ms	8	10,000	2000	Omni

Long Term Trends in Ocean Noise

What is the long-term trend for ocean noise? Overall trends of the level of sounds in the sea can be broken down into anthropogenic and non-anthropogenic components. For instance, there is evidence that global climate change may have resulted in higher sea states (Bacon and Carter 1993; Graham and Diaz 2001), which would increase ambient noise levels. Over the past few decades, however, it is likely that increases in anthropogenic noise have been more prominent. In order of importance, the anthropogenic sources most likely to have contributed to increased noise are: commercial shipping, offshore oil and gas exploration and drilling, and naval and other uses of sonar.

To isolate the effects of anthropogenic and non-anthropogenic noise, waters surrounding Australia, which are remote from commercial shipping, have been examined. At low frequency (100 Hz), Australian data suggest that ocean noise levels may be as low as 50 dB re 1μPa^2/Hz, which is about 30 to 40 dB below levels in North American and European waters ((Cato and McCauley 2002)). These data further suggest that wind/wave noise increases at low frequencies, in contrast to the predictions of the deepwater curves developed from northern hemisphere data (Wenz 1962). Cato (2001, from NRC2003) points to the difficulty of separating wind/wave-generated noise from shipping noise in North American datasets.

Trends in ambient noise over the past few decades suggest that sound levels have increased by 10 dB or more between 1950 and 1975 (Ross 1987, 1993). These trends are most apparent in the eastern Pacific and eastern and western Atlantic, where they are attributed to increases in commercial shipping. A doubling of the number of ships explains 3 to 5 dB, and greater average ship speeds, propulsion power, and propeller tip speeds explain an additional 6 dB.

Other data on long-term noise trends come from comparison of historical U.S. Navy acoustic array data (Wenz 1969) with modern recordings along the west coast of North America (Andrew et al. 2002). A low-frequency noise increase of 10 dB over 33 years is observed at a site off the central California coast. The explanation for a noise increase in this band is the growth in commercial shipping, in terms of both number of ships and gross tonnage. From 1972 to 1999 the total number of ships in the world's fleet increased from approximately 57,000 to 87,000, and the total gross tonnage increased from 268 to 543 million gross tons.

Mazzuca (2001) compared the results of Wenz (1969), Ross (1987), and Andrew (2002) to derive an overall increase of 16 dB in low-frequency noise from 1950 to 2000. This corresponds to a doubling of noise power (3 dB) every decade for the past five decades, equivalent to a 7 percent annual increase in noise. During this period the number of ships in the world fleet tripled (from 30,000 to 87,000) and the gross tonnage increased by a factor of 6.5 (from 85 to 550 million gross tons) (NRC 2003; from (McCarthy and Miller 2002).

Ocean Noise Research Priorities

Ocean noise is an important component of the marine habitat. Data on ocean noise trends are scarce, however, despite substantial investment by the U.S. government in underwater sound data collection for military purposes (e.g. SOSUS and other ASW monitoring systems). Informed estimates suggest noise has increased significantly during the past few decades. Expanding use of the sea for commercial shipping and advanced warfare has resulted in noise levels are at least 10 times higher today than they were a few decades ago. Without some effort to monitor, reduce or at least cap these noise levels, they are likely to increase and further degrade the acoustic environment of marine mammals. A summary of recommendations for tracking and improving our understanding of ocean noise sources are presented in Table 4.

Table 4. Research Priorities for Understanding and Tracking Ocean Noise.	
Priority	**Research Topic**
1	Initiate long-term ocean noise monitoring programs
2	Collect, organize, and analyze historic marine anthropogenic noise data
3	Develop global models for ocean noise
4	Report signal characteristics for anthropogenic noise sources
5	Determine the relationship between anthropogenic activity level and noise level

Priority 1: Initiate long-term ocean noise monitoring

A long-term monitoring program is needed to track future changes in ocean noise (NRC 2003:90). Acoustic data should be included in global ocean observing systems now being developed by U.S. and international research foundations. Data from these monitoring systems should be openly available, and presented in a manner accessible to decision makers in industry, in the military, and in regulatory agencies.

Priority 2: analyze historic marine anthropogenic noise data

In tandem with the effort to collect and monitor present-day ocean noise, a database should be developed to collect, organize and standardize data on ocean noise measurements and related anthropogenic activities (NRC 2003:89). Infrastructure already is in place that is appropriate for maintaining an archive of these data (e.g. the National Oceanographic Data Center, www.nodc.noaa.gov). Currently, data regarding shipping, seismic exploration, oil and gas production, and other marine activities are either not collected or are difficult to obtain and analyze because they are maintained by separate organizations. International cooperation in this effort should be encouraged.

Priority 3: Develop global models for ocean noise

Marine noise measurements and anthropogenic source data should be used to develop a global model of ocean noise (NRC 2003:92). This model should incorporate both transient events, and continuous noise sources. The development an accurate global model depends on access to ocean noise data and anthropogenic activity data, as described for the database research priority above.

Priority 4: Report signal characteristics for anthropogenic noise sources

An important component of model development is better understanding of the signal characteristics for representative anthropogenic noise sources. The description of these signals should include enough information to allow reconstruction of its character (e.g. frequency content, pressure and/or particle-velocity time series, duration, repetition rate).

Priority 5: Determine the relationship between anthropogenic activity level and noise level

Research should be conducted relating the overall levels of anthropogenic activity (such as the types and numbers of vessels) with the resulting noise (NRC 2003:90). These relations will help to extend noise modeling to areas without direct long-term monitoring, but where anthropogenic noise sources are present.

HOW NOISE AFFECTS MARINE MAMMALS

The response of marine mammals to sound depends upon a range of factors including: (1) the sound pressure level and other properties (e.g., frequency, duration, novelty), (2) the physical and behavioral state of the animals, and (3) the ambient acoustic and ecological features of the environment (see Richardson et al. 1995 for a review of marine mammal responses to specific noise sources). No comprehensive understanding of marine mammal responses to noise is available, either to predict how marine mammals respond behaviorally to intense sounds, or to long-term increases in ambient noise.

In humans, the perceived loudness level of a sound involves not only hearing sensitivity but also psychological/physiological factors (Beranek and Ver 1992). A loudness-level scale has been developed from detailed testing where the human subject judges the relative loudness of two sounds. For instance, the phon (in dB) compares the loudness level of a 1 kHz tone to tones of varying frequency. In practice the annoyance level of a sound depends upon a range of factors in addition to loudness, such as the sound's fluctuation. Intermittent sounds are more annoying than continuous ones. How reliably human noise studies can be extrapolated to marine mammals is problematic, of course, in view of the vast differences in the role of sound in sensing the marine and terrestrial environments.

Marine mammal sound production

The frequency band of noise that may be important to marine mammals should approximately match the range of the sounds that they produce. For large mysticetes, sound production is in the low-frequency range of 10 to 1,000 Hz, whereas for small odontocetes, sound production is in the mid- and high-frequency range of 1 to 200 kHz. Marine mammal call frequencies show an inverse correlation with body size (Watkins and Wartzok 1985), Richardson et al. 1995, Wartzok and Ketten 1999).

Odontocetes produce (a) broadband clicks with peak energy between 5 and 150 kHz, varying by species, (b) burst-pulse click trains, and (c) tonal or frequency-modulated whistles that range from 1 to 25 kHz. Mysticetes generally produce low-frequency sounds in the range 10 Hz to 2 kHz. Mysticete sounds can be broadly characterized as (a) tonal calls, (b) frequency-modulated sweeps, and (c) pulsed tonals. These sounds can be generated either as individual calls or combined into patterned sequences or songs. Pinnipeds that breed on land produce a limited range of barks and clicks ranging from <1 to 4 kHz. Those that mate in the water produce complex vocalizations during the breeding season. All pinnipeds, the sea otter, and manatees use sound to establish and maintain the mother-young bond, especially when attempting to reunite after separation (Sandegren et al. 1973; Hartman 1979).

The ability to use self-generated sounds to obtain information about objects and features of the environment — echolocation — has been demonstrated for at least 13 odontocete species (Richardson et al. 1995). No odontocete has been shown to be incapable of echolocation. Based on their echolocation signals, odontocetes have been divided into two acoustic groups: (a) type I species produce clicks with peak spectra above 100 kHz and few whistles, and (b) type II species produce clicks with peak spectra below 80 kHz and use whistles regularly (Ketten and Wartzok 1990). Type I odontocetes are inshore and riverine delphinids that operate in acoustically complex environments. Examples are Amazon river dolphins (*Inia geoffrensis)* that sometimes hunt small fish in the flooded forest (Norris et al. 1972) and harbor porpoises (*Phocoena phocoena)* that live primarily in shallow, near-shore waters (Kamminga 1988).

Type II odontocetes include nearshore and offshore species that inhabit environments with low object densities and that engage in conspecific communication. Examples are bottlenose dolphins (*Tursiops truncates*), which are coastal, and pantropical spotted dolphins (*Stenella* spp.*)*, which often occur in offshore waters. There is some suggestion of a negative correlation between body size and the maximum frequency of whistles (Ding et al. 1995). Odontocete whistles have been described as "signature" calls which identify individuals (Caldwell and Caldwell 1965). Likewise burst-pulse sounds produced by killer whales are group-specific (Tyack 2000) and click train codas in sperm whales show geographic variation (Rendell and Whitehead 2003).

Source levels for odontocete clicks have been reported to be as high as 228 dB re 1µPa @ 1 m for false killer whales (*Pseudorca crassidens)* (Thomas and Turl 1990) and for bottlenose dolphins echolocating in the presence of noise (Au 1993) and 232 dB re 1µPa @ 1 m for male sperm whale (*Physeter macrocephalus*) clicks (Mohl et al. 2000). The short duration of these echolocation clicks (50 to 200 µs) means that their total energy is low (197 dB re 1µPa^2-sec) although their source levels are high. Odontocete whistles have lower source levels than their clicks, ranging from less than 110 dB re 1µPa @ 1 m for the spinner dolphin (*Stenella longirostris*) (Watkins and Schevill 1974) to 169 dB re 1µPa @ 1 m for bottlenose dolphins (Janik 2000) and 180 dB re 1µPa @ 1 m for short-finned pilot whales (*Globicephala macrorhychus*) (Fish and Turl 1976). The detection range for odontocete clicks and whistles may be 1 km or less, although much greater detection ranges also have been reported (Leaper et al. 1992; Barlow and Taylor 1998; Gordon et al. 2000).

Mysticete calls can be detected over long ranges (Payne and Webb 1971). For instance, blue whales (*Balaenoptera musculus*) produce low-frequency (10 to100 Hz) calls with estimated source levels of 185 dB re 1µPa @ 1 m (McDonald et al. 2001). Most large mysticetes (blue, fin, bowhead, right, humpback, Bryde's, and gray whale) are known to vocalize at frequencies below 1 kHz, with estimated source levels as high as 180 dB re 1µPa @ 1 m (Richardson et al. 1995).

Source levels and frequencies have been estimated for the underwater calls of several species of pinnipeds. Examples are the Weddell seal (*Leptonychotes weddellii*), which produces calls from 148 to 193 dB re 1µPa @ 1 m at frequencies of 0.2 to 12.8 kHz (Thomas and Kuechle 1982), and the Ross seal (*Ommatophoca rossi*), which produces calls at 1 to 4 kHz (Watkins and Ray 1985). These calls may be detected at ranges of several kilometers both in the open ocean and under ice (Wartzok et al. 1992).

Marine mammal hearing

Sound propagates efficiently underwater, and one reflection of its importance to marine mammals is their development of broader hearing frequency ranges than is typical for land mammals. Audiograms have been produced for 10 species of odontocetes and 11 species of pinnipeds, out of a total of approximately 119 marine mammal species (data are summarized by Wartzok and Ketten 1999). All hearing data are from species that are small enough to be held in captivity. Direct hearing data are not available for the species that are not readily tested by conventional audiometric methods. For these species, audiograms must be estimated from mathematical models based on ear anatomy or inferred from the sounds they produce and from field exposure experiments.

Most odontocetes have functional hearing from 200 Hz to 100 kHz, and some species may hear frequencies as high as 200 kHz. Odontocete hearing has peak sensitivity between 20 and 80 kHz, along with moderate sensitivity in the 1–20 kHz range. Because ambient noise decreases at high frequencies, odontocetes may find an advantage in having their hearing and echolocation at high a frequency to filter out as much of the low-frequency noise as possible.

Based on modeling but with no measured audiograms, mysticete hearing ranges between 20 Hz and 20-30 kHz. Several of the larger species, such as blue and fin whales, are predicted to hear at infrasonic (10 Hz) frequencies. Pinnipeds have their best hearing between 1 and 20 kHz, with the exception of the northern elephant seal, which has good hearing below 1 kHz (Kastak and Schusterman 1998). Some pinnipeds hear moderately well in both water and air, while others are better adapted for underwater than for in-air hearing.

Marine mammal hearing is adapted to an aquatic environment, yet their inner ears resemble those of land mammals. The divergence in hearing physiology between land and marine mammals is most pronounced in the external ears, which are absent in most marine mammal species, and in the middle ears, which are extensively modified in marine mammals. Because hearing loss in land mammals is often related to physical damage to the inner ear, hearing loss in marine mammals may involve similar mechanisms. Because ambient noise in the sea can vary by many orders of magnitude due to storms and other natural phenomena, marine mammals may have developed resilient inner ears to guard against hearing loss. Existing studies do not allow for prediction of the impacts of high-intensity sounds on marine mammal hearing except in general terms.

Hearing Losses

Hearing thresholds for hearing may be degraded by exposure to high-intensity sound. Hearing losses are classified as either temporary threshold shifts (TTS) or permanent threshold shifts (PTS), where repeated TTS may lead to PTS. The extent of hearing loss is related to the sound power spectrum, the hearing sensitivity, and the duration of exposure. High-intensity, impulsive blasts can damage cetacean ears (Ketten et al. 1993). Hearing losses may result in poor conspecific communication, lessened abilities for echolocation and foraging, and erratic behavior with respect to migration, mating, stranding, and vulnerability to predators. For cetaceans, which are highly dependent on their acoustic sense, both TTS and PTS must be considered serious.

There are relatively few data on hearing loss in marine mammals. Experiments on captive bottlenose dolphins (Ridgway et al. 1997) suggest that TTS is observed at levels of 193 to 196 dB re 1µPa for exposure to 1-second tones at 20 kHz. Recent work by (Finneran et al. 2002) with impulsive sources (seismic waterguns) suggest that exposure to sound pressure levels of 217 dB dB re 1µPa and total energy fluxes of 186 dB dB re 1µPa^{2}s produces TTS in beluga whales (*Delphinaptera leucas*). One assumption is that animals are most vulnerable to TTS at the frequencies of their greatest hearing sensitivity. For baleen whales, this suggests low-frequency sensitivity and for smaller cetaceans, mid- and high-frequency sensitivity. It also raises the question of why marine mammals (apparently) do not damage their hearing by their own sound production, as both the tonal and impulsive sounds that they produce can be comparable in SPL to those found to induce TTS in the controlled experiments mentioned above. It appears that there are internal mechanisms that protect an animal from its own vocalisations. For instance, the pterygoid sinus cavities of odontocetes may be positioned to shield their inner ears from their own sound production.

Noise Masking

Acoustic signals are detected against a background of ambient noise. When background noise increases, it may reduce an animal's ability to detect relevant sound, called noise masking. Noise is effective for masking when it is within a critical band (CB) of frequency around the desired signal. The amount by which a pure tone must exceed the noise spectral level to be audible is called the critical ratio (CR). The CR is related to the bandwidth within which background noise affects the animal's ability to detect a sound. Estimates of marine mammal CBs and CRs come from captive odontocetes and pinnipeds (Richardson et al. 1995). For all species, when CB is plotted as a function of frequency, there is a steep rise at low frequencies (25 – 75 percent at 100 Hz), and a much lower level (1 – 10 percent) at mid and high frequencies (1 – 100 kHz). This suggests that narrow-band noise is more effective at masking low frequencies than mid and high frequencies. An animal's directional hearing capabilities may aid in avoiding masking by resolving the different directions of propagation between the signal and the noise. A directivity index of as much as 20 dB has been measured for bottlenose dolphins (Au and Moore 1984), whereas directional hearing is less acute in pinnipeds.

Masking of beluga whale sounds by icebreaker noise has been studied (Erbe and Farmer 1998; Erbe 2000; Erbe and Farmer 2000), including construction of software to model this process (Erbe et al. 1999). Icebreaker noise from ramming, ice cracking, and bubbler systems were shown to produce masking at noise-to-signal ratios of 30 to 800 (15 to 29 dB). The predicted zone of masking for beluga calls from ramming noise was 40 km (Erbe and Farmer 2000). Beluga whales' vocal output changes when they are moved to locations with higher background noise. With noise at low frequencies, an animal increases both the sound pressure level and the frequency of its vocalizations, perhaps in an attempt to avoid masking. Beluga whales also have been observed to increase call rates and shift to higher call frequencies in response to boat noise (Lesage et al. 1999).

Hearing Development

Is increased noise in the oceans causing developmental problems for young animals? High-noise environments affect speech and language development in very young rats (Chang and Merzenich 2003). Brain circuits that receive and interpret sound did not develop at the same rate in animals living in an environment of continuous background noise as in animals that were raised in a quiet environment. It took three to four times as long for rats raised in a noisy environment to reach the basic benchmarks of auditory development. For marine mammals, these data may be difficult to obtain but should be an important consideration of the potential impact of ocean noise.

Effects of Noise on Marine Mammal Behavior

The behavioral responses of marine mammals to noise are complex and poorly understood (Richardson et al. 1995). They may depend upon hearing sensitivity, behavioral state, habituation or desensitization, age, sex, presence of offspring, location of exposure, and proximity to a shoreline. Behavioral responses may range from subtle changes in surfacing and breathing patterns to cessation of vocalization to active avoidance or escape from the region of highest sound levels. For instance, several studies suggest that bowhead whales (*Balaena mysticetus*) follow a pattern of shorter surfacings, shorter dives, fewer blows per surfacing, and longer intervals between blows when exposed to anthropogenic noise, even at moderate received levels (114 dB re 1µPa). Another common response pattern is a reduction or cessation of vocalization, such as for right whales (*Eubalaena* spp.) in response to boat noise (Watkins 1986), bowheads in response to playback of industrial sounds (Wartzok et al. 1989), sperm whales in response to pulses from acoustic pingers (Watkins and Schevill 1975) and in the presence of military sonar (Watkins et al. 1985), and sperm and pilot whales in response to the Heard Island test acoustic source (Bowles et al. 1994). Moreover, humpback whales (*Megaptera novaeangliae*) lengthen their song cycles when exposed to the LFA source (Miller et al. 2000), move away from mid-frequency sonar (Maybaum 1993), and tend to cease vocalizations when near boats (Watkins 1986). Beluga whales adjust their echolocation clicks to higher frequencies and higher source levels in the presence of increased background noise (Au et al. 1985). Gray whales (*Eschrichtius robustus*) exhibited an avoidance response when exposed to airgun noise, and their response became more as the source level increased from 164 to 180 dB re 1µPa (Malme et al. 1984). They also preferentially avoided LFA transmissions conducted in a landward direction (Tyack and Clark 1998).

Marine mammals have also been observed to have little or no reaction to some anthropogenic sounds. For example, sperm whales continued calling when they encountered echosounders (Watkins 1977) and when they were exposed to received sound levels of 180 dB re 1µPa from a detonator (Madsen and Mohl 2000). A fin whale (*Balaenoptera physalus*) continued to call with no change in rate, level, or frequency in the presence of noise from a container ship (Edds 1988).

Age and sex are important factors in marine mammal noise sensitivity. For instance, juvenile and pregnant northern sea lions (*Eumetopias jubatus*) are more likely to leave a haul-out site in response to aircraft overflights than are territory-holding males and females with young (Calkins 1979). Walruses (*Odobenus rosmarus*) may stampede and crush calves (Loughrey 1959) or temporarily abandon calves (Fay et al. 1984) when exposed to sounds from aircraft or vessels. Likewise, in gray whales cow-calf pairs are more sensitive than other age or sex classes to disturbance by whale-watching boats (Tilt 1985), and humpback groups containing at least one calf are more sensitive to vessel traffic than are groups without calves (Bauer et al. 1993).

Marine mammal responses also appear to be affected by the location, motion, and type of onset of a sound source. California sea lions (*Zalophus californianus*) and harbor seals (*Phoca vitulina*) react at greater range from a ship when they are hauled out, and this is also true of walruses (Fay et al. 1984). Bowheads are more responsive to overflights of aircraft when they are in shallow water (Richardson and Malme 1993). Fin whales are more tolerant of a stationary than a moving source (Watkins 1986). Humpback whales are less likely to react to a continuous source than to one with a sudden onset (Malme et al. 1985). In the St. Lawrence River, beluga whales are less likely to change their swimming and diving patterns in the presence of vessels moving at low speed than in the presence of fast-moving boats (Blane and Jaakson 1994). In Alaska, beluga whales feeding on river salmon may stop and move downstream in response to noise from small boats, whereas they are relatively unresponsive to noise from fishing boats (Stewart et al. 1982). In Bristol Bay beluga whales continue to feed even when surrounded by fishing vessels, and they may resist dispersal even when purposely harassed (Fish and Vania 1971).

Few studies document long-term responses to anthropogenic noise by marine mammals. At Guerrero Negro Lagoon in Baja California, shipping and dredging noise associated with a salt works may have induced gray whales to abandon the area through most of the 1960s (Bryant et al. 1984). After ship traffic declined, the lagoon was reoccupied, first by single whales and later by cow-calf pairs. Killer whales (*Orcinus orca*) in the British Columbia region were displaced from Broughton Archipelago during 1993-1999, a period when acoustic harassment devices were in use at existing salmon farms (Morton and Symonds 2002).

Habituation and tolerance of noise

Habituation is the loss of sensitivity to noise over time. The best evidence for habituation of marine mammals to intense sound comes from attempts to use acoustic harassment devices (AHDs) to keep marine mammals away from aquaculture facilities or fishing equipment (Jefferson and Curry 1994). For instance, there is some evidence that harbor seals habituate to AHDs, partly because they modify their swimming behavior to keep their heads out of the water when they are in high-intensity sound fields (Mate and Harvey 1987). Likewise, harbor porpoises have been shown to habituate to gillnet pingers over a span of 10 or 11 days (Cox et al. 2002).

Observations of responses to whale-watching and other vessels also suggest some level of habituation to noise. Near Cape Cod, minke whales (*Balaenoptera acutorostrata)* changed from being attracted to vessels to appearing generally uninterested; fin whales from flight reactions to disinterest, and humpback whales from mixed but usually strongly negative to strongly positive reactions (Watkins 1986). At San Ignacio Lagoon, gray whales become less likely to flee from whale-watching boats as the season progresses (Jones and Swartz 1984).

Habituation does not signify that hearing loss or injury from high-intensity sounds has not occurred. Humpback whales found in Newfoundland remained in a feeding area near where seafloor blasting was being conducted (Todd et al. 1996). Received sound pressure levels at 1 mile from the explosions were typically 145-150 dB re 1µPa at 240-450 Hz, with presumed source levels of 295-300 dB re 1µPa at 1 m. The whales showed no clear reaction to the blasting in terms of behavior, movement, or residence time. However, increased entrapment in nets followed the blast exposure (Todd et al. 1996). In addition, two whales were found dead after a 5000-kg explosion, and examination of the temporal bones of their inner ears revealed significant blast trauma (Ketten et al. 1993). This incident highlights the difficulty of using overt behavioral reactions to monitor marine mammal harassment by noise or high intensity sound.

Incidents of Mass Stranding Associated with High-Intensity Sound

On several occasions multiple-animal strandings have been associated with the use of high-intensity sonar during naval operations and airguns during seismic reflection profiling. Most of these incidents involved Cuvier's beaked whales (*Ziphius cavirostris)*. At many of these sites, Cuvier's beaked whale is not thought to be the most abundant cetacean species present.

Only odontocetes are known to mass strand, that is, to come ashore in groups of two or more animals (Walsh et al. 2001). Mass strandings of beaked whales are relatively rare events. The National Museum of Natural History, Smithsonian Institution (James Mead, pers. comm.) has compiled a global list of *Ziphius cavirostris* strandings involving two or more animals (Table 5). Except for a stranding of two individuals in 1914, there are no records of multiple-animal strandings until 1963. However, from 1960 to 2000, 3 to 10 multi-animal strandings have been recorded per decade.

The first published suggestion of a connection between beaked whale strandings and naval activity was by (Simmonds and Lopez-Jurado 1991). They described a set of three multi-animal strandings associated with naval activity in the Canary Islands in 1985, 1988, and 1989. Additional incidents of beaked whale mass strandings in the Canary Islands were noted in 1986 and 1987. Simmonds and Lopez-Jurado (1991) did not draw a connection between beaked whale mass strandings and the use of ASW sonar, but rather to the nearby presence of naval operations.

The increased incidence of multi-animal beaked whale stranding events indeed may be correlated with the advent of high-intensity sonar. Prototypes of hull-mounted ASW sonars (e.g., SQS-23 and 26) were first tested in 1957 (Gerken 1986) and were deployed on a broad range of naval ships (frigates, cruisers, and destroyers) operated by the United States and other nations beginning in the early 1960s. This timing coincides with increased reports of mass strandings of Cuvier's beaked whales (Table 5). A third (11 of 32) of the documented strandings of *Ziphius cavirostris* strandings are associated with concurrent naval activities.

An examination of the circumstances surrounding mass strandings of beaked whales may help to define their relationship with the use of high-intensity sound. Two such strandings have been documented by investigative reports: the Kryparissiakos Gulf, Greece, incident of May 1996 (D'Amico and Verboom 1998), and the Bahamas incident of March 2000 (Evans and England 2001). Examination of other beaked whale mass strandings provides additional perspective on the diversity of sound sources, environment, and conditions associated with these events.

Table 5. Strandings involving at least two *Ziphius cavirostris* (Zc) from Smithsonian records (James Mead, pers. comm., with author updates). These represent the only known multiple stranding events for *Mesoplodon europaeus* (Me) and *Mesoplodon densirostris* (Md).

Year	Location	Species (numbers)	Correlated Activity
1914	United States (NY)	Zc (2)	
1963	Italy	Zc (15+)	
1965	Puerto Rico	Zc (5)	
1968	Bahamas	Zc (4)	
1974	Corsica	Zc (3), *Stenella coeruleoalba* (1)	Naval patrol
1974	Lesser Antilles	Zc (4)	Naval explosion
1975	Lesser Antilles	Zc (3)	
1980	Bahamas	Zc (3)	
1981	Bermuda	Zc (4)	
1981	United States (AK)	Zc (2)	
1983	Galapagos	Zc (6)	
1985	Canary Islands	Zc (12+), Me (1)	Naval maneuvers
1986	Canary Islands	Zc (5), Me (1)	
1987	Canary Islands	Zc (group), Me (2)	
1987	Italy	Zc (2)	
1988	Canary Islands	Zc (3), Me (1), *Hyperoodon ampullatus* (1), *Kogia breviceps* (2)	Naval maneuvers
1989	Canary Islands	Zc (19+), Me (2), Md (3)	Naval maneuvers
1991	Canary Islands	Zc (2)	Naval maneuvers
1991	Lesser Antilles	Zc (4)	
1993	Taiwan	Zc (2)	
1994	Taiwan	Zc (2)	
1996	Greece	Zc (12)	Navy LFAS trials
1997	Greece	Zc (3)	
1997	Greece	Zc (8)	
1998	Puerto Rico	Zc (5)	
2000	Bahamas	Zc (9), Md (3), ziphiid sp. (2), *Balaenoptera acutorostrata* (2), *Stenella frontalis* (1)	Naval maneuvers
2000	Galapagos	Zc (3)	Seismic airgun
2000	Madeira	Zc (3)	Naval maneuvers
2001	Solomon Islands	Zc (2)	
2002	Canary Islands	Zc (7), Me (2), Md (1), ziphiid sp. (9)	Naval maneuvers
2002	Baja California	Zc (2)	Seismic airgun
2003	Australia	Zc (2+)	Naval maneuvers

Kryparissiakos Gulf, Greece, May 1996

Frantzis (1998) first brought attention to a mass stranding of Cuvier's beaked whales in the Ionian Sea, which coincided with tests of an ASW sonar (LFAS) by the North Atlantic Treaty Organization (NATO). Along 56 km of coastline, 14 *Ziphius cavirostris* stranded during 12–13 May 1996. Twelve of 14 animals stranded alive, with no apparent disease or pathogenic cause. These strandings corresponded with a four-day period (12–16 May) when the vessel *NRV Alliance* was towing an acoustic source in the vicinity. The acoustic source generated both low-frequency and mid-frequency sound at source levels of 226 dB re 1µPa @ 1m. The transmitted low-frequency signal included a 2 sec upsweep at 450-650 Hz, and a 2 sec cw tone at 700 Hz. The mid-frequency signal included a 2 sec upsweep at 2.8-3.2 kHz and a 2 sec tone at 3.3 kHz. Both sources projected horizontally directed beams of sound with vertical beamwidths of about 23 degrees. Three source tows of about 2 hours duration were conducted each day; and the strandings occurred most closely in time with the first two source runs of 12 May (runs 9 and 10, D'Amico and Verboom [1998]) and the last two source runs of 13 May (runs 13 and 14, D'Amico and Verboom [1998]).

The association of stranding locations and acoustic source tracks in space and time is compelling evidence that these animals were affected by the ASW sonar (D'Amico and Verboom 1998). Figure 1 shows the acoustic source tracks and stranding locations for 12 and 13 May. There is a general correlation between the offshore source track locations and the inshore stranding locations. The 13 May source tow track is shifted northward from the 12 May track, and likewise some of the 13 May stranding locations are farther north. Correlation of stranding times and source track locations for 12 May suggests that at least three of the six animals with known stranding times were affected by the 0600-0800 source tow (run 9) as their stranding times precede the 1100-1300 source tow (run 10). Assuming that they were near the source when they were exposed to a high sound level, their swimming distances were approximately 30 nm to reach the shore, covered at speeds of approximately 10 knots. The two strandings in the afternoon of 12 May with known times likewise required swimming distances of 20-30 nm.

Bahamas, March 15 -16, 2000

Sixteen cetaceans were found stranded along the Providence Channel in the Bahamas Islands during a two-day period in March 2000. This mass stranding correlated with a U.S. Navy training exercise using ASW sonar (Evans and England 2001). The stranded animals were predominantly beaked whales (*Z. cavirostris* [9], *Mesoplodon densirostris* [3]), and *Ziphiid* sp. [2]). At least two minke whales (*Balaenoptera acutorostrata)* were also found stranded. One dolphin *(Stenella frontalis)* stranded at a somewhat distant location and may have died of unrelated causes. Eight of the beaked whales died, and the remaining animals were refloated and their fate is unknown. None of these animals has been recognized as restranded or resighted (Balcomb and Claridge 2001). Tissue samples were collected from five of the dead beaked whales. Gross necropsy results suggested that all five were in good body condition; none showed evidence of debilitating disease. Some kind of auditory damage was found in four of the beaked whales examined. Hemorrhages were found in the acoustic fats of the head, the inner ears, and some spaces around the brain, with no evidence of external blunt force trauma. The pattern of injury in the freshest specimens suggested that the ears were structurally intact and the animals were alive at the time of injury (Evans and England 2001).

Four U.S. Navy ships were operating hull-mounted ASW sonars in the area, two SQS-53C and two SQS-56. The SQS-53C sonars were operated at 2.6 and 3.3 kHz with a source level of 235 dB re 1µPa @ 1 m or higher, and 0.5 - 2 sec ping lengths alternating between tones and frequency-modulated sweeps. The SQS-56 sonars were operated at 6.8, 7.5, and 8.2 KHz at 223 dB re 1µPa @ 1 m. Integrated sound exposure levels >160 dB for 10-30 sec were found throughout much of the Providence Channel during 15 March 2000 (Evans and England 2001).

The association of stranding locations and acoustic source tracks in space and time is compelling evidence that these animals were affected by the high-intensity sound sources (Evans and England 2001). The acoustic source tracks and stranding locations are shown in Figure 2, divided into the morning (0700-1100) and afternoon (1200-1430). During the morning two source ships were in the Providence Channel off the southwest end of Abaco Island and moving toward the west, and the other two source ships were entering the channel from the east. A cluster of strandings occurred at the south end of Abaco Island during this time, at minimum ranges of 10-30 nm from the ships' closest points of approach. During the afternoon, the source ships moved northwestward, approaching Grand Bahama Island. A cluster of noon and afternoon strandings occurred on the south coast of Grand Bahama Island, again with minimum source-to-shore ranges of 20-30 nm. Assuming that these animals received peak sound exposures at locations near the source tracks, then immediately following exposure they would have swum toward the stranding sites at high speed (~ 10 kts). Alternatively, lower exposure levels more distant from the source tracks and closer to the stranding sites would imply slower swim speeds.

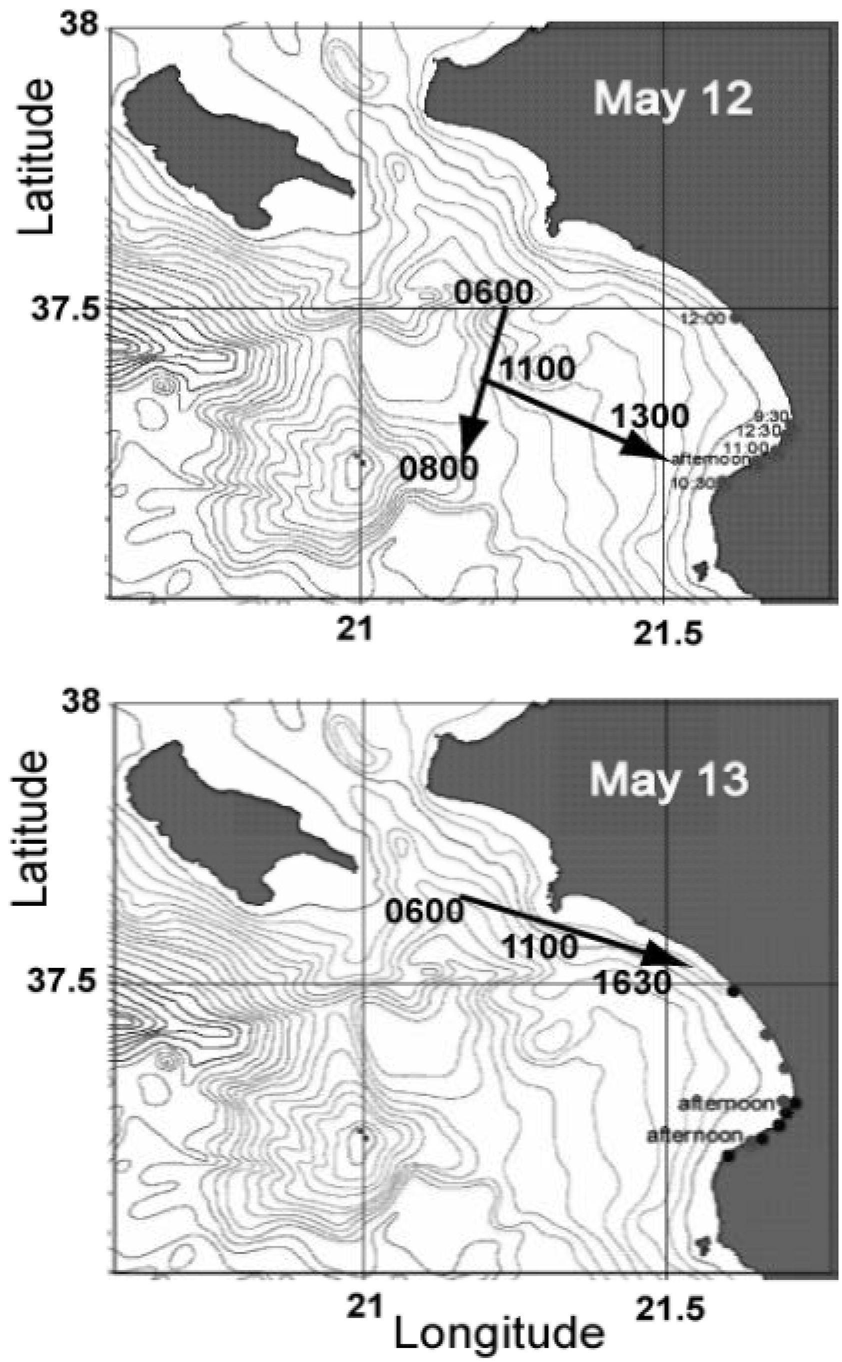
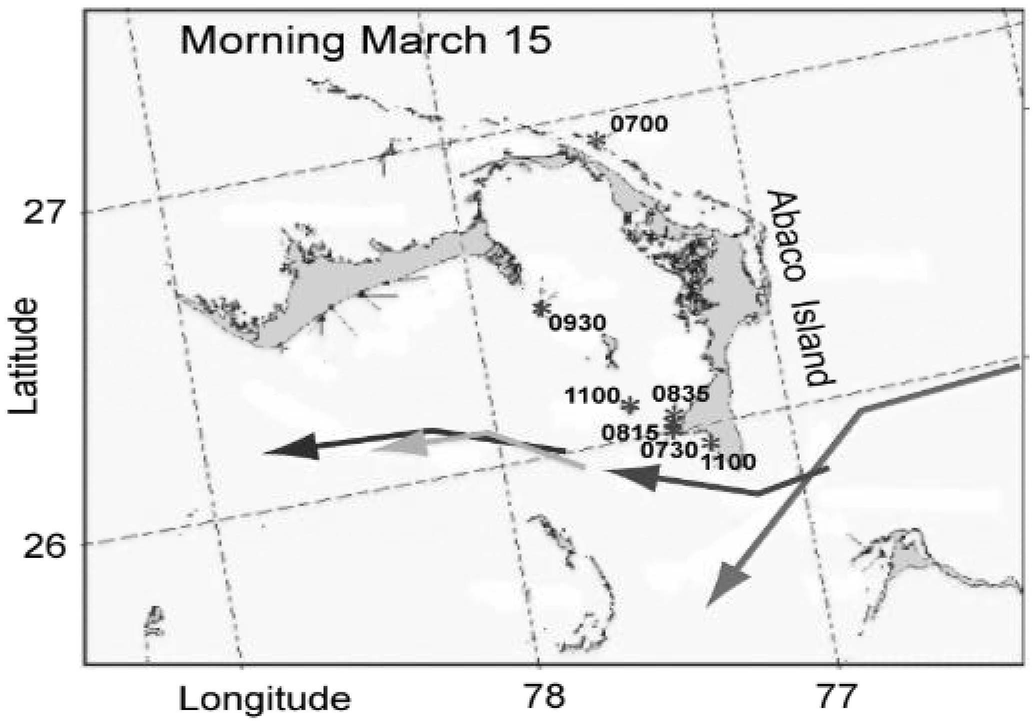


Figure 1. Kyparissiakos Gulf, Greece, *Ziphius cavirostris* stranding locations and acoustic source tracks for 12 May (upper) and 13 May (lower) 1996. Known times are indicated in GMT.



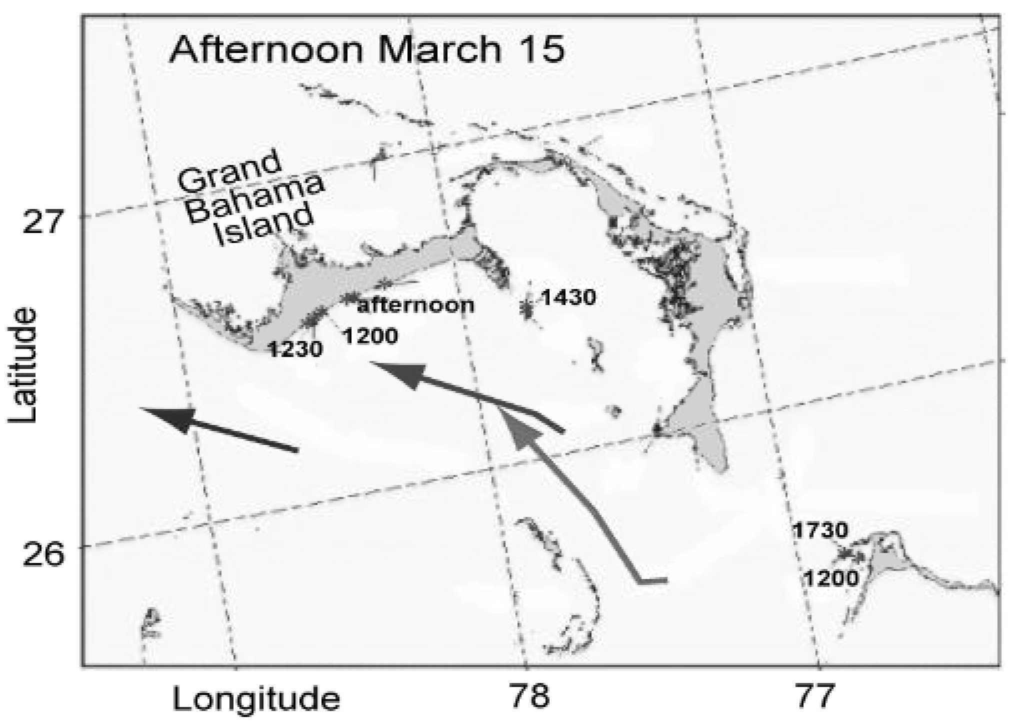


Figure 2. Bahamas strandings locations and acoustic source tracks for 15 March 2000, morning (upper) and afternoon (lower). Known times are indicated in GMT.

Madeira, May 2000

A stranding of three *Ziphius cavirostris* occurred in May 2000 on the Madeira Archipelago, in the northeastern Atlantic (Luis Freitas, Madeira Whale Museum, pers. comm.). The deep-water channel between islands has been the site of repeated observations of live *Z. cavirostris*. The animals that stranded in May 2000 consisted of two subadults (one male, one female) and a female of unknown age. The two subadults were examined and found to have hematomas, eye hemorrhages, pleural hemorrhages, and lesions of the lungs (Luis Freitas, pers. comm.). The third animal was found in an advanced state of decomposition and did not receive a detailed examination. The presence of a NATO exercise was signaled by naval vessels and aircraft in the deep-water channel, coincident with the stranding events. Details of the acoustic sources in use during this exercise are lacking at this time.

Canary Islands, 24 September 2002

A mass stranding of as many as 19 beaked whales occurred on the Canary Islands of Fuerteventura and Lanzarote, associated with naval maneuvers by Spain and other NATO countries on 24–25 September 2002. The stranded animals were predominantly *Ziphius cavirostris* (7), but also included *Mesoplodon europaeus* (2) and *Mesoplodon densirostris* (1). On 24 September a total of 14 animals were found stranded; five were dead, three were alive and subsequently died, and six were pushed back to sea. Five more animals were found dead and in a state of decomposition between 25 and 28 September. It is possible that these included animals that had been pushed out to sea and subsequently stranded . Preliminary necropsy results for six of the beaked whales suggest that they were healthy. The strandings occurred at dawn or in the early morning, and the animals that were found alive all appeared disoriented. Those that were found dead had been feeding recently (Vidal Martín and Antonella Servidio, pers. comm.).

Necropsies and dissections revealed no visible signs of trauma (Antonio Fernández, Universidad de Las Palmas de Gran Canaria). Hemorrhages were observed along acoustic paths and in the brain and spinal cord. All animals were bleeding profusely in the eyes. Multifocal petechial (pinpoint) hemorrhages were observed, similar to decompression sickness. Fat embolism was observed, which could have been responsible for hemorrhages in the macrovascular system. Degeneration (in vivo) of vestibucochlear portions of the ear were noted, specifically, degeneration and resorption of some hair cell bundles and associated nerve fibers. This may suggest a chronic condition, and that some damage to the cochlea had occurred prior to this stranding event.

The strandings occurred along the southeastern coast of the islands of Fuerteventura and Lanzarote. At the time of the 24–25 September strandings, 10 NATO countries — Germany, Belgium, Canada, France, Greece, Norway, Portugal, Britain, Turkey, and the United States — were conducting a multinational naval exercise; however, the acoustic sources employed during the exercise are not known at this time. There have been seven mass strandings of *Z. cavirostris* in the Canary Islands since 1985, and naval exercises have been recorded as associated with five of them (Table 5).

Gulf of California, 24 September 2002

A stranding of two *Ziphius cavirostris* occurred on 24 September 2002 on Isla San Jose in the Gulf of California, Mexico, coincident with seismic reflection profiling by the *R/V Maurice Ewing* operated by Columbia University, Lamont-Doherty Earth Observatory (Malakoff 2002). On 24 September at about 2 to 4 PM local time (2100–2300 GMT), fishermen discovered two live stranded whales and unsuccessfully attempted to push them back out to sea (Jorge Urbán, pers. comm.). A group of marine biologists found the whales dead on 25 September (Barbara Taylor, pers. comm.). By 27 September, when one carcass was necropsied, the advanced state of decomposition did not allow the cause of death to be determined.

On 24September the *R/V Ewing* had been firing an array of 20 airguns with a total volume of 8500 cubic inches. These airguns have an equivalent broadband source level of 256 dB re 1µPa @ 1m, with peak energy frequencies at 40-100 Hz. Source levels at mid-frequencies (1-5 kHz) may be diminished by 20 to 40 dB (Goold and Fish 1998). The airguns were fired with an approximately 20 sec repetition rate (50 m distance between shots). Figure 3 indicates the ship track for 24–25 September; the *R/V Ewing* was on a transect line directed toward the stranding site and reached the closest point-of-approach (within 22 km) at 1400 local time (2100 GMT) range.

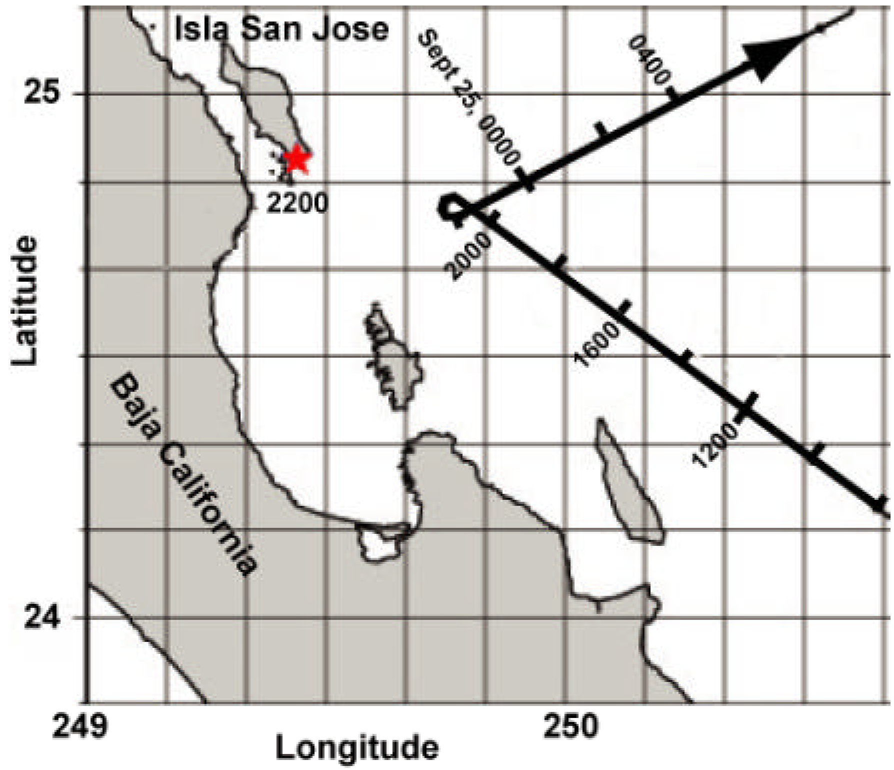


Figure 3. Gulf of California standings location and acoustic source tracks for 24–25 September 2002. Times are indicated in GMT.

Summary of Beaked Whale Stranding Events

Repeated mass strandings of beaked whales following high-intensity sound exposure demonstrate a pattern of events. Cuvier's beaked whales are, by far, the most common species involved in these stranding events; they make up 81 percent of the total number of stranded animals. Other beaked whales (including *Mesoplodon europaeus*, *Mesoplodon densirostris,* and *Hyperoodon ampullatus)* comprise 14 percent of the total, and other species (*Stenella coeruleoalba*, *Kogia breviceps,* and *Balaenoptera acutorostrata*) are sparsely represented. It is not clear whether (a) *Ziphius cavirostris* is more prone to injury from high-intensity sound than other species, (b) its behavioral response to sound makes it more likely to strand, or (c) it is substantially more abundant than the other affected species in the areas and times of the exposures leading to the mass strandings. One, two, or three of these possibilities could apply. In any event, *Ziphius cavirostris* has proven to be the "miner's canary" for high-intensity sound impacts. The simultaneous deployment of naval ASW sonars in the 1960s and the coincident increase in *Ziphius cavirostris* mass strandings suggest that lethal impacts of anthropogenic sound on cetaceans have been occurring for at least several decades.

The settings for these incidents are strikingly consistent: an island or archipelago with deep water nearby, appropriate for beaked whale foraging habitat. The conditions for mass stranding may be optimized when the sound source transits a deep channel between two islands, such as in the Bahamas incident. When exposed to high sound levels, beaked whales rapidly swim to the nearest beach. The animals appear on the beach not as one tight cluster of individuals but rather distributed over miles of coastline. Hypothermia ensues, and the animals die if they are not returned to the sea by human intervention. The fates of those animals that are returned to the sea are unknown. Necropsies of stranded animals suggest internal bleeding in the eyes, ears, and brain, as well as fat embolisms.

The implicated sound levels involve long-duration (~ 1 sec) and high-intensity (235 dB re 1µPa @ 1 m) sonar pings or equivalent airgun blasts. Mid-frequency (1-6 kHz) sound is clearly implicated in the sonar-induced stranding incidents. It is unclear whether low-frequency sound also causes injury to beaked whales. Although airguns create predominantly low-frequency energy, they also have ample mid-frequency energy, which may be related to the associated injuries.

Research Priorities for Marine Mammal Noise Effects

Almost a decade has passed since the NRC (1994) outlined a set of research priorities for understanding the effect of noise on marine mammals. In most of the areas outlined for study by the NRC (1994) report, we still lack basic understanding. Many of the same research priorities were reiterated by two subsequent NRC (2000, 2003) reports directed at understanding marine mammal noise impacts. The need to conduct most of these noise impact studies in the field, rather than in captive settings, means that it may be many years before a clear understanding of these issues becomes available. There is an additional need to differentiate those effects that are significant to individual animals from those that are significant on a population level. This distinction points to the need for observations that are distributed in space and time, and involve large numbers of cases to create strong statistics. With these issues in mind, Table 6 summarizes key research priorities needed to diminish the uncertainties associated with anthropogenic noise production and the protection of marine mammals.

Table 6. Summary of Research Priorities for the Effect of Noise on Marine Mammals.

Priority	Research Issue
1	Understand the detailed causes of beaked whale mass stranding events
2	Determine behavioral responses to anthropogenic sound
3	Improve tools for marine mammal behavioral observation including acoustic recording tags and passive acoustic methods
4	Develop tools to study marine mammal physiology in the wild including stress indicators and hearing capabilities
5	Characterization of marine mammal populations within areas of high intensity sound generation

Priority 1: Understand the causes of beaked whale mass stranding events

When exposed to high intensity sound levels, beaked whales strand and die in mass. Understanding the causes and consequences of beaked whale mass stranding represents the highest research priority for our community. The sound levels implicated in these events is probably not sufficient to cause permanent hearing threshold shifts. What is the mechanism for damage and/or disturbance? The behavioral reaction is swift, and vigorous on an individual level. The lack of close animal clustering on the beach suggests little or no social component to these stranding, yet the potential for large numbers of stranded animals suggests significance at a population level. What are the source parameters that lead to damage? Is low frequency sound (the primary energy component of airguns) as damaging as mid frequency sound (used by SQS-53 ASW tactical sonars)? What sound pressure exposure level creates damage and/or disturbance? Beaked whale mass stranding events make it abundantly clear that high intensity anthropogenic sound is a threat to marine mammals, yet there are key parameters that we must understand about beaked whale strandings before we can predict the impact of high intensity sound on other species in other settings.

Priority 2: Determine behavioral responses to anthropogenic sound

A key impediment to assessing the biological effects of ocean noise is a continued lack of knowledge about marine mammal behavior in general, and lack of understanding their behavioral response to anthropogenic sound in particular. Behavioral data must be collected in the wild to provide a full picture of the potential effects. Significant ocean noise effects may be confined to a few individuals exposed at high sound pressure levels, and/or from widespread exposure at a population level. Controlled exposure experiments may be helpful in defining obvious and/or short term impacts to individuals, but may not reveal long term impacts. Discerning population level effects is challenging since the observations must be conducted over broad distances and long time periods. Relating migration and movement to noise level is one potential approach. Do marine mammals systematically avoid habitat areas with high noise levels? More subtle behavioral changes may be associated with exposure to high ambient ocean noise. Is natural sound (e.g. snapping of shrimp) useful for prey location? A better understanding of how and why marine mammals make and use sound would greatly aid or ability to predict how ocean noise might be disruptive to marine mammal behavior. The sound avoidance reaction of marine mammals has been exploited to exclude them from fisheries interactions by acoustic harassment devices, but does their behavioral reaction occur before losses to their hearing? Our lack of understanding marine mammal behavioral reaction to sound is vast and must be addressed in the face of raising ocean noise levels.

Priority 3: Improve tools for marine mammal behavioral observation

Research tools are needed to better observe marine mammal behavior in the wild. These are needed both to characterize normal behaviors and to detect changes in behavior associated with anthropogenic noise. Marine mammal acoustic recording tags are an important technology for detailed behavioral studies in the presence of noise. Technical improvements are needed over current tags to increase their duration of attachment, to expand the volume of stored data and to enhance the suite of available sensors. Tag attachment system improvements are particularly needed for large cetaceans than cannot be captured for tag emplacement. Current non-invasive attachments have limited duration, whereas invasive attachments involve both damage and disturbance to the animal. Technology for passive acoustic tracking of animals is another important component of behavioral study with the potential for future improvement.

Priority 4: Develop tools to study marine mammal physiology in the wild

For many species of marine mammal it is unlikely that large number of individual animals will be kept in captivity for study of their physiology. Tools are needed to study marine mammal physiology in the wild. For instance, indicators of stress may be one way to assess the impact of anthropogenic noise on marine mammals. If stress factors can be measured fromblubber or blood samples, perhaps biopsy of other tissue samples collected in the wild could reveal regional or population-wide stress levels associated with noise. Likewise, without a rapidly deployed field method for determination of hearing capabilities, it will be difficult to collect audiometric data on the full range of marine mammal species and under conditions were chronic noise may have degraded hearing capabilities. The ability to collect audiometric data on beached or ensnared animals would be a first step, particularly useful when high intensity sound may be suspected in the animals' stranding.

Priority 5: Marine mammal populations within areas of high intensity sound generation

Anthropogenic ocean noise sources are primarily concentrated into a few well defined zones: (1) at major commercial ports and along shipping lanes, and (2) within military test and training sites. The marine mammal populations within these zones should be characterized and monitored for potential impact due to anthropogenic noise. A combination of both visual and acoustic monitoring may provide an efficient means for monitoring both marine mammal distributions and ambient noise. These data will further aid efforts to determine if ocean noise is a factor in discouraging habitat use by marine mammals.

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